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Fox, Paul D.; Smith, Penny Probert

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Buffer Rod Design for Measurement of Specific Gravity in the Processing of Industrial Food Batters

Paul D Fox* Penny Probert Smith† Sarabjit S Sahi‡

Abstract - A low cost perspex buffer rod design for the measurement of specific gravity during the processing of industrial food batters is reported. Operation was conducted in pulsed mode using a 2.25MHz, 15mm diameter transducer and the intensity and an analytic calibration curve relating buffer rod output to specific gravity is obtained. The probe design may have application to other similar mixtures or industrial sludges in which similar material properties are observed.

I INTRODUCTION

In food batters, the incorporation of air in a finely dispersed form has an important influence on its properties, including appearance, texture, consistency and size per unit weight. In fact the presence of a well-defined volume of gas cells can be essential for the characteristic properties of that particular food [1]. In this study we concentrate on high ratio industrial cake batters consisting of cake flour, sugar, fat, milk powder, salt, egg, glycerine and water. The amount of air beaten into in these batters during the mixing process is reflected in a change of specific gravity of the batter and determines to a large extent the overall quality of the cake [2], as well as affecting cake volume [3] and rheological flow properties [4]. The specific gravity of the batter varies as a function of mixing time, and here we focus on the initial drop in specific gravity since this is the phase during which mixing is terminated in the industrial mixers. The traditional method for establishing the stopping time is to halt the process periodically, remove and manually weigh a batter sample of fixed volume in order to determine its specific gravity (S_b). This is a time consuming and labor intensive process, which ideally could be replaced by an automated ultrasonic device online without human intervention. In this article we report a low cost perspex buffer rod design for this purpose.

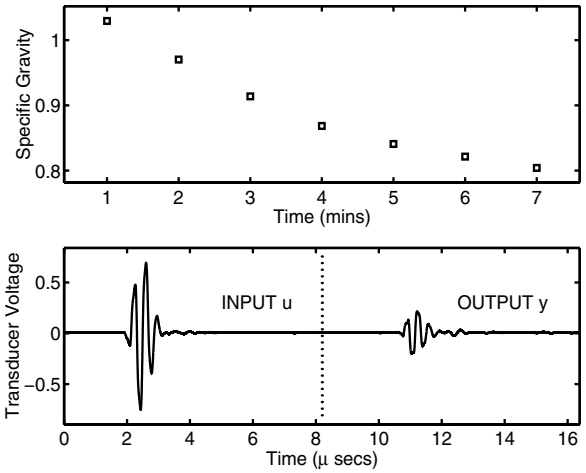

Figure 1: *Upper plot* : Manually measured specific gravity versus time for Mix 1. *Lower plot* : Typical input-output transducer voltage time series at a given measuring instant. Left time window is considered as input signal and right window as output signal.

Prior to mixing, all ingredients are originally equilibrated to 21°C prior to mixing and slowly blended together at a low mixing speed for an initial period of 90 seconds in order to achieve batter homogeneity. The measured mixing then takes place in blocks of 60 second periods, and the batter density is measured by determining the weight of batter within a container of known volume (Figure 1, upper). At each point in time, the probe is also inserted into the batter, with the probe out-

*Center for Fast Ultrasound Imaging, Ørsted-DTU, Building 348, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark. (pdf@oersted.dtu.dk)

†Robotics Research Group, Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK. (pjp@robots.ox.ac.uk)

‡Campden & Chorleywood Food Research Association, Chipping Campden, GL55 6LD, UK. (s.sahi@campden.co.uk)

put voltage being a time series of the form of Figure 1 (lower). The objective is then to deduce an ultrasonic measure of the specific gravity which can provide a calibration for future use of the probe without the need to measure specific gravity manually.

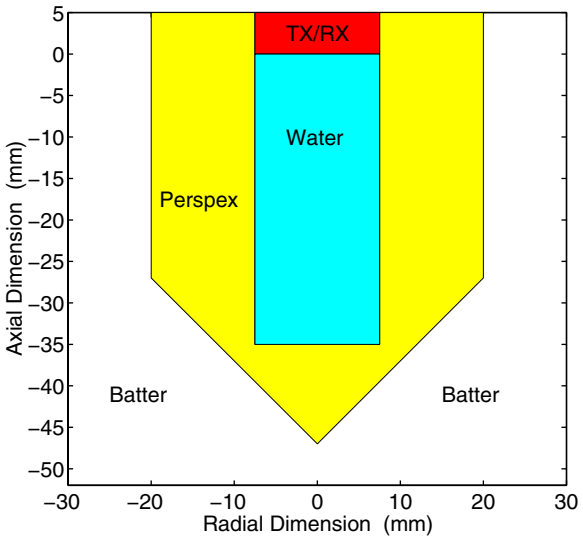

Figure 2: Schematic cut through probe centerline.

II PROBE ANALYSIS

Construction of the probe was as per Figure 2. This simple low-cost design consists of a perspex outer chamber housing an internal 2.25MHz 15mm diameter transducer (TX/RX) and water chamber, which are separated from the batter by means of the perspex housing. This housing is terminated in the form of a 45^o conical tip such that it enters the batter cleanly without trapping any external air bubbles on the outer surface as it enters into the batter sample. To analyse the probe behaviour, we use the standard model for a plane wave passing from the first medium ('f') to the second medium ('s') with the following reflection and transmission coefficients R_{fs} and T_{fs} :

$$R_{fs} = \frac{\rho_s c_s \cos\theta_{fs} - \rho_f c_f \cos\phi_{fs}}{\rho_s c_s \cos\theta_{fs} + \rho_f c_f \cos\phi_{fs}} \quad (1)$$

$$T_{fs} = \frac{2\rho_s c_s \cos\theta_{fs}}{\rho_s c_s \cos\theta_{fs} + \rho_f c_f \cos\phi_{fs}} \quad (2)$$

Here ρ_f, ρ_s and c_f, c_s are the densities and velocities for media f and s respectively. The angles θ_{fs} are the incident impact/reflection angle in medium f and ϕ_{fs} is the propagation angle into medium s. Snell's law also relates ϕ_{fs} to θ_{fs} via the velocities c_f, c_s as $\sin\phi_{fs} = (c_s \sin\theta_{fs})/c_f$. Then, neglecting any losses in the water and perspex, the following reflection-transmission sequence (summarised in Table 1) is assumed. Firstly a

Table 1: Summary of Reflection and Transmission Sequences

Interface Sequence	Reflected Pressure	Transmitted Pressure
1. Water-Perspex	$R_{wp}P$	$T_{wp}P$
2. Perspex-Batter	$R_{pb}T_{wp}P$	$T_{pb}T_{wp}P$
3. Perspex-Batter	$R_{pb}^2T_{wp}P$	$T_{pb}R_{pb}T_{wp}P$
4. Perspex-Water	$R_{pw}R_{pb}^2T_{wp}P$	$T_{pw}R_{pb}^2T_{wp}P$

pulsed wave of instantaneous amplitude P travels down the water channel and impacts upon the water-perspex interface. An amount $R_{wp}P$ is then reflected back to the transducer giving rise to a measured ('input') voltage $u = HR_{wp}P$ where H is the transducer transfer function at the frequency of interest. A pressure $T_{wp}P$ is transmitted through the interface into the perspex and then impacts against the 45^o perspex-batter interface. A pressure $R_{pb}T_{wp}P$ is then reflected back into the perspex whilst a pressure $T_{pb}T_{wp}P$ transmitted into the batter at an unknown transmission angle ϕ_{pb}. The reflected pressure $R_{pb}T_{wp}P$ then travels through the perspex across to the other tip face, where the same perspex-batter interaction takes place once again. This gives a reflected pressure $R_{pb}^2T_{wp}P$ into the perspex and transmitted pressure $T_{pb}R_{pb}T_{wp}P$ into the batter. Finally the wave of pressure $R_{pb}^2T_{wp}P$ impacts the perspex-water interface, with pressure $R_{pw}R_{pb}^2T_{wp}P$ being reflected back into the perspex and pressure $T_{pw}R_{pb}^2T_{wp}P$ being transmitted through into the water channel.The transmitted wave travels to the transducer surface and gives rise to a measured ('output') voltage of $y = HT_{pw}R_{pb}^2T_{wp}P$. The probe gain G at a given frequency is then defined as the ratio of output y to input u

$$G = \frac{T_{pw}R_{pb}^2T_{wp}}{R_{wp}} \quad (3)$$

for which the component terms are listed in Table 2.

Table 2: Known and unknown process parameters

Medium	Density $\left(\frac{kg}{m^3}\right)$	Velocity $\left(\frac{m}{s}\right)$
Water	$\rho_w = 1000$	$c_w = 1480$
Perspex	$\rho_p = 1176$	$c_p = 2730$
Batter	$\rho_b = ?$	$c_b = ?$

Interface	Incidence/Reflection Angle (degrees)	Transmission Angle (degrees)
Water-Perspex	$\theta_{wp} = 0$	$\phi_{wp} = 0$
Perspex-Water	$\theta_{pw} = 0$	$\phi_{pw} = 0$
Perspex-Batter	$\theta_{pb} = 45$	$\phi_{pb} = ?$

Interface	$\gamma\left(\times 10^{-7}\frac{m^2 s}{kg}\right)$	$\delta\left(\times 10^{-4}\frac{s}{m}\right)$
Water-Perspex	$\gamma_{wp} = 6.7568$	$\delta_{wp} = 3.6630$
Perspex-Water	$\gamma_{pw} = 3.1148$	$\delta_{pw} = 6.7568$
Perspex-Batter	$\gamma_{pb} = 2.2025$	$\delta_{pb} = ?$

Interface	Reflection Coefficient R	Transmission Coefficient T
Water-Perspex	$R_{wp} = 0.3689$	$T_{wp} = 1.3689$
Perspex-Water	$R_{pw} = -0.3689$	$T_{pw} = 0.6311$
Perspex-Batter	$R_{pb} = ?$	$T_{pb} = ?$

Notice that the reflection coefficient R_{pb} for the interface between perspex and batter is unknown. Notice also that the gain G in equation (3) general varies as a function of both pulse component frequency and mixing time. Figure 3 (upper) shows this behaviour, in which the lower line represents the gain at different frequencies after one minute of mixing (time t_1) and the upper line represents the gain after 7 minutes of mixing (time t_7). For the remaining analysis we then choose to operate at a given frequency, in which a component just over 2MHz was found to give the most reliable results in practice. Figure 3 (lower) shows gain at this frequency against mixing time, with the experimentally measured relationship between gain and specific being given in Figure 4 (upper). Substituting for R_{pb} from (1) by replacing subscripts 'f 'and 's 'with 'p' and 'b' for perspex and batter respectively to the batter specific gravity $S_b = \rho_b/\rho_w$ as

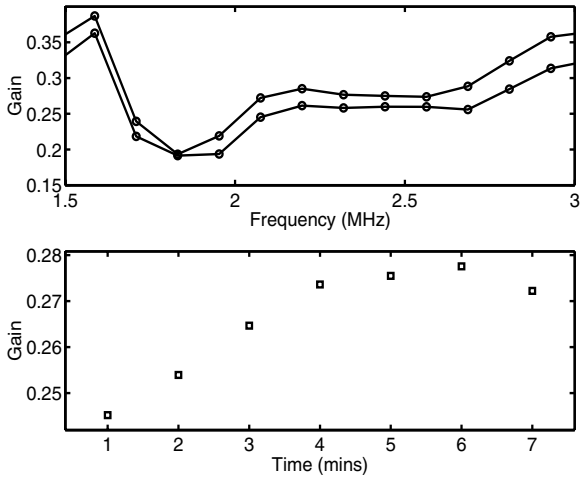

Figure 3: $Upper\ plot$: Gain magnitudes vs frequency for Mix 1 at times t_1 (lower line) and t_7 (upper line). $Lower\ plot$: Transducer gain G at $2.0752MHz$ versus time for Mix 1.

$$S_b = \delta_{pb} \times \frac{1 + K\sqrt{G}}{\gamma_{pb}\rho_w\left(1 - K\sqrt{G}\right)} \quad : \quad \delta_{pb} = \frac{\cos\phi_{pb}}{c_b} \tag{4}$$

where $\gamma_{pb} = (\cos\theta_{pb})/\rho_p c_p$ and $K = \sqrt{R_{wp}/T_{wp}T_{pw}}$ and ρ_w are known but δ_{pb} is unknown since both c_b and ϕ_{pb} are unknown. Hence S_b cannot be obtained in practice from equation (4) until a reasonable estimate of δ_{pb} is obtained, achievable by rearranging (6) to give

$$\delta_{pb} = S_b \times \frac{\gamma_{pb}\rho_w\left(1 - K\sqrt{G}\right)}{1 + K\sqrt{G}} \tag{5}$$

Note then that the right hand side of this equation may then be plotted from the measured values of gain G and specific gravity S_b for a given 'calibration' data set (Lower plot, Figure 4). This function may be well approximated in by a straight line of the form $\delta_{pb} \approx \alpha + \beta S_b$ in the region of interest (where $\alpha = 7.5597 \times 10^{-5}$ and $\beta = 3.5898 \times 10^{-4}$ for a least squares fit). Substituting for δ_{pb} into equation (5) and rearranging then gives

$$\alpha + \beta S_b \approx S_b \times \frac{\gamma_{pb}\rho_w\left(1 - K\sqrt{G}\right)}{1 + K\sqrt{G}} \tag{6}$$

from which we obtain a final calibrated estimate of the specific gravity for subsequent batter samples as

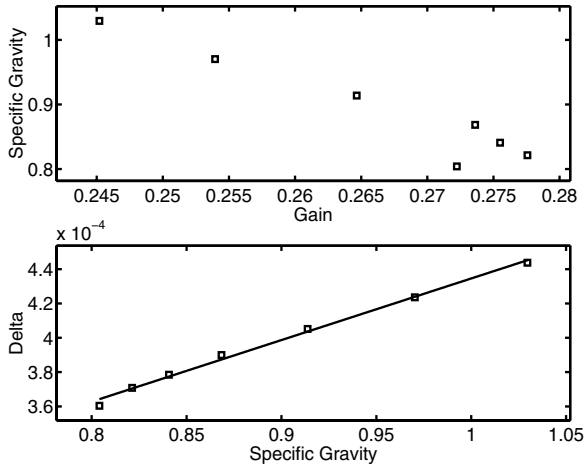

Figure 4: *Upper plot* : Specific gravity versus gain for Mix 1. *Lower plot* : Delta versus specific gravity for Mix 1.

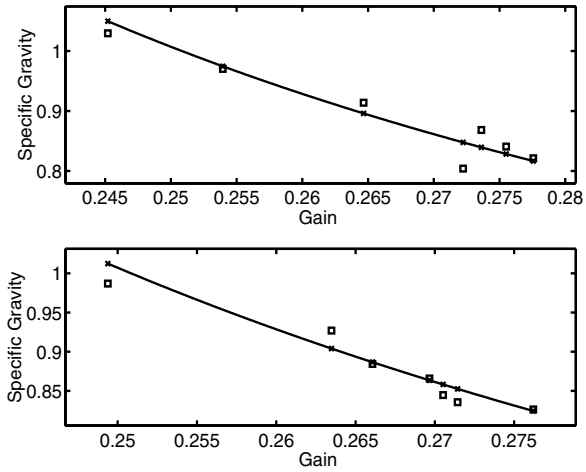

Figure 5: *Upper plot* : Measured and calibrated specific gravities versus gain for Mix 1. *Lower plot* : Estimated and measured specific gravity for Mix 2.

$$\hat{S}_b = \frac{\alpha}{\gamma_{pb}\rho_w \left(\dfrac{1 - K\sqrt{G}}{1 + K\sqrt{G}} \right) - \beta} \tag{7}$$

where $\hat{S}_b$ represents the estimate of S_b obtained by removing the approximation sign from (6). Figure 5 (upper) shows the resulting $\hat{S}_b$ calibration curve obtained from Mix 1, and Figure 5 (lower) then shows estimates $\hat{S}_b$ for a second mix, in which the α and β parameters from Mix 1 have been used to generate the estimates for the second Mix from equation (7). In both cases the estimated specific gravities fit the measured data well.

III Conclusions

The buffer rod proved successful as a technique to measure properties at the interface to a high viscosity, air filled mixture which did not support significant transmission. The general design may also have application to measurement of specific gravity in a wider array of industrial substances.

IV Acknowledgments

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